

HARD PHOTONS AND NEUTRAL PIONS FROM RHIC

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In order to fix the parameters for predictions of hard photon and pion production in $Au + Au$ collisions at $\sqrt{s} = 200$ GeV, proton-proton and proton-nucleus data are analyzed in perturbative QCD in the energy range $\sqrt{s} \approx 20 - 60$ GeV.

1 Introduction

Interest in direct photon production at RHIC^{1,2} is motivated by the long mean free path of photons. Hard photon production can be calculated in the pQCD-improved parton model. Experiments need to separate the direct photons from the π^0 (and ω^0) two-photon background. It is estimated that the direct photon yield has to be at least 10% of the π^0 yield to be measurable. We have embarked on the following project: (i) fix the pQCD description of γ and π^0 production in pp collisions; (ii) address nuclear effects in pA collisions; (iii) calculate direct γ and π^0 production in AA collisions at $\sqrt{s} = 200$ GeV. Our first results, which pertain to (i) and (ii), are summarized in Ref. 3.

Parton cross sections are calculable in pQCD at high energy to leading order (LO) or next-to-leading-order (NLO).^{4,5} The parton distribution functions (PDFs) and fragmentation functions (FFs), however, need to be fitted to data. In recent NLO calculations the various scales are optimized.⁶ Alternatively, an additional non-perturbative parameter, the width of the *intrinsic transverse momentum* (k_T) distribution of the partons is introduced.⁷ We choose the latter method and use k_T phenomenologically in pp collisions, expecting that its importance will decrease in higher orders of pQCD.

2 Proton-proton collisions

In the lowest-order pQCD-improved parton model, direct pion production can be described in pp collisions by

$$E_\pi \frac{d\sigma_\pi^{pp}}{d^3p} = \sum_{abcd} \int dx_{1,2} f_1(x_1, Q^2) f_2(x_2, Q^2) K \frac{d\sigma}{dt}(ab \rightarrow cd) \frac{D(z_c, \hat{Q}^2)}{\pi z_c} \quad , \quad (1)$$

where $f_1(x, Q^2)$ and $f_2(x, Q^2)$ are the PDFs of partons a and b , and σ is the LO cross section of the appropriate partonic subprocess. The K-factor accounts for higher order corrections.⁸ Comparing LO and NLO calculations a nearly constant value, $K \approx 2$, is obtained as a good approximation of the higher order contributions in the p_T region of interest.⁹ In eq.(1) $D(z_c, \hat{Q}^2)$ is the FF of the pion, with $\hat{Q} = p_T/z_c$, where z_c is the momentum fraction of the final hadron. We use NLO parameterizations of the PDFs¹⁰ and FFs¹¹ with fixed scales. Direct γ production is described similarly.⁴

To incorporate the intrinsic k_T , each integral is extended to k_T -space, $dx f(x, Q^2) \rightarrow dx d^2k_T g(\vec{k}_T) f(x, Q^2)$.^{9,12} We approximate $g(\vec{k}_T)$ as $g(\vec{k}_T) = \exp(-k_T^2/\langle k_T^2 \rangle)/\pi\langle k_T^2 \rangle$. Here $\langle k_T^2 \rangle$ is the 2-dimensional width of the k_T distribution, related to the average k_T of one parton as $\langle k_T^2 \rangle = 4\langle k_T \rangle^2/\pi$.

We applied this model to data from $pp \rightarrow \pi^0 X$ and $pp \rightarrow \gamma X$.^{13,14,15} The calculations were corrected for the finite rapidity windows of the data. The Monte-Carlo integrals were carried out by the standard VEGAS routine.¹⁶ We fitted the data minimizing $\Delta^2 = \sum (Data - Theory)^2 / Theory^2$ in the midpoints of the data. Fig. 1. shows the obtained fit values for $\langle k_T^2 \rangle$ and a calculated $\langle k_T \rangle$. The error bars display a $\Delta^2 = \Delta_{min}^2 \pm 0.1$ uncertainty in the fit procedure. The lines guide the eye and indicate a linear increase to a common value of $\langle k_T \rangle \approx 3.5$ GeV at $\sqrt{s} = 1800$ GeV.¹⁷

These values of $\langle k_T \rangle$ provide a satisfactory description of the data up to energies of $\sqrt{s} \approx 65$ GeV. The data/theory ratios cluster around unity, with no systematic trend in the deviations (different experiments show different

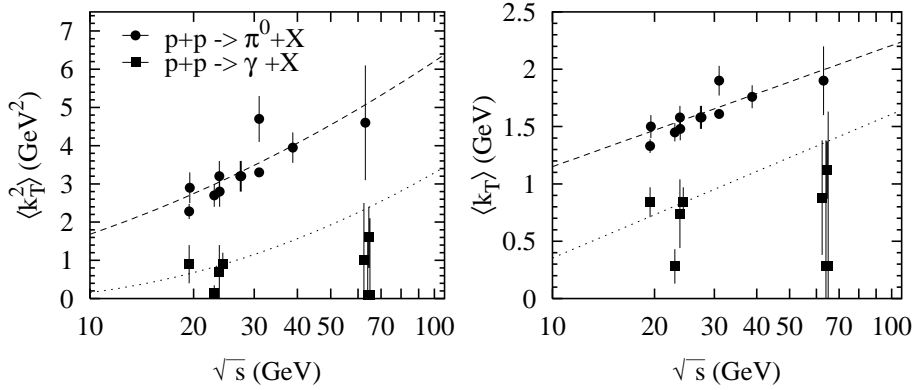


Figure 1. Best fits for the widths of the intrinsic transverse momentum distributions in γ and π^0 production data in pp collisions as a function of cm energy. See text for the lines.

slopes).^{3,18} The maximum deviations are on the order of $\approx 50\%$.

To estimate the p_T value where the direct photon production cross section surpasses 10% of the pion cross section in a pp collision at $\sqrt{s} = 200$ GeV, we use the \sqrt{s} dependence of $\langle k_T \rangle$ from Fig. 1, and obtain the results displayed in Fig. 2. The threshold is reached in this approximation at $p_T \approx 6.5$ GeV.

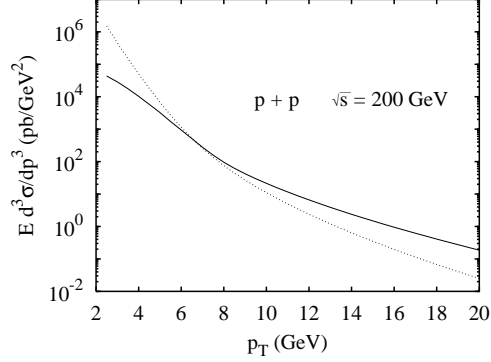


Figure 2. Extrapolated γ (full line) and $\pi^0(\times 0.1)$ (dashed) production cross sections as functions of transverse momentum in pp collisions at $\sqrt{s} = 200$ GeV.

3 Proton-nucleus collisions

Having isolated the $\langle k_T^2 \rangle$ already present in π^0 and γ production in pp collisions at the present level of calculation, we turn to the nuclear enhancement observed¹³ in pA collisions. In minimum-biased pA collisions the pQCD description of the inclusive pion cross section is based on

$$E_\pi \frac{d\sigma_\pi^{pA}}{d^3p} = \sum_{abcd} \int d^2b t_A(b) \int dx_{1,2} d^2k_{T_{1,2}} g_1(\vec{k}_{T_1}, b) g_2(\vec{k}_{T_2}) f_1(x_1, Q^2) f_2(x_2, Q^2) K \frac{d\sigma}{d\hat{t}} \frac{D(z_c, \hat{Q}^2)}{\pi z_c}. \quad (2)$$

Here b is the impact parameter and $t_A(b)$ is the nuclear thickness function normalized as $\int d^2b t_A(b) = A$. For simplicity, we use a sharp sphere nucleus with $t_A(b) = 2\rho_0 \sqrt{R_A^2 - b^2}$, where $R_A = 1.14A^{1/3}$ and $\rho_0 = 0.16 \text{ fm}^{-3}$.

The standard physical explanation of the nuclear enhancement (Cronin effect) is that the proton traveling through the nucleus gains extra transverse momentum due to random soft collisions and the partons enter the final hard

process with this extra k_T .¹² We write the width of the transverse momentum distribution of the partons in the incoming proton as

$$\langle k_T^2 \rangle_{pA} = \langle k_T^2 \rangle_{pp} + C \cdot h_{pA}(b) . \quad (3)$$

Here $h_{pA}(b)$ is the number of *effective* nucleon-nucleon collisions at impact parameter b imparting an average transverse momentum squared C . Naively all possible soft interactions are included, but such a picture leads to a target-dependent C .³ A more satisfactory description is obtained with a “saturated” h_{pA} , where it takes at most one semi-hard ($Q^2 \sim 1 \text{ GeV}^2$) collision for the incoming proton to loose coherence, resulting in an increase of the width of its k_T distribution. This is approximated by a smoothed step function with a maximum value of unity. The saturated Cronin factor is denoted by C^{sat} .

As displayed in the left of Fig. 3, $C^{sat} = 1.2 \text{ GeV}^2$ gives a good fit of $pA \rightarrow \pi^0 X$ data with $A = Be, Ti$ and W .¹³ The right panel of Fig. 3 illustrates how $C^{sat} = 1.2 \text{ GeV}^2$ describes γ production at $\sqrt{s} \approx 30 - 40 \text{ GeV}$.

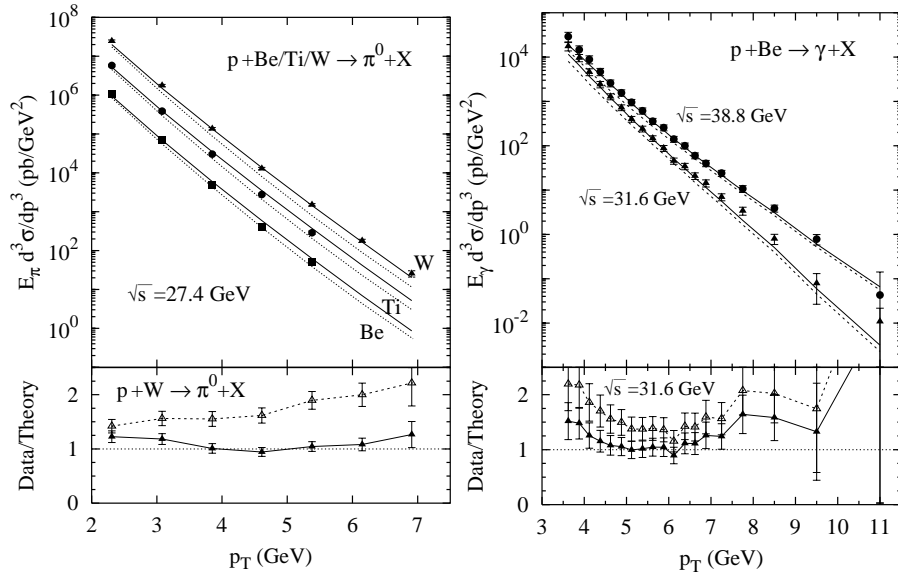


Figure 3. *Left:* Cross section per nucleon in $pA \rightarrow \pi^0 X$ reactions ($A = Be, Ti, W$). We show $C^{sat} = 1.2 \text{ GeV}^2$ (full lines) and $C^{sat} = 0$ (dashed lines). Lower panel: data/theory on a linear scale for the pW collision. *Right:* Cross section per nucleon in the $pBe \rightarrow \gamma X$ reaction at two energies.¹⁹ Solid lines indicate $C^{sat} = 1.2 \text{ GeV}^2$, dashed lines mean $C^{sat} = 0$. Lower panel shows data/theory for $\sqrt{s} = 31.6 \text{ GeV}$.

We interpret C^{sat} as the square of the typical transverse momentum imparted in *one* semi-hard collision prior to the hard scattering. This picture and the energy dependence of C^{sat} need to be tested as functions of A at different energies, and in particular at $\sqrt{s} = 200$ GeV, for RHIC AA predictions.

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